STORING CARBON IN

S. Julio Friedmann

"We have met the enemy, and he is us."
Walt Kelly's *Pogo*

"In the fields of observation, chance favors only the mind that is prepared."
Louis Pasteur

The dilemma is rather straightforward. We are finding more evidence that fossil fuel consumption has produced global warming and climate change, and that continued burning of fossil fuels will make things worse. The most compelling write-up of this sentiment comes from the Intergovernmental Panel on Climate Change (IPCC) 2001 document, which not only outlines the astonishing depth and variety of evidence to this effect, but also presents simple yet grim predictions about the likeliest changes to sea level, surface temperature and rainfall patterns.

At the same time, it seems equally clear that fossil fuel is a vital fixture for our future. The abundance and high energy content of fossil fuels make them unparalleled in terms of cost, convenience and ease of use. Moreover, the rapid growth in energy demand in the United States and abroad makes fossil fuels essential for continued economic growth and human well being. Unfortunately, consumption of these energy sources produces carbon dioxide, the longest lived and most problematic of greenhouse emissions.

The way forward will require a reduction of carbon emissions, continued or increased fossil fuel consumption, and economic and population growth for 50 to 100 years. This combination leads us to three options: efficiency improvements, emissions reduction engineering or carbon sequestration. The third option is where geoscientists can have the largest impact.

Carbon sequestration is capturing carbon dioxide, either from the atmosphere or emission streams, and storing it in reservoirs, such as plants or soils. Carbon dioxide could be converted to solid chemicals

EARTH

UNDER THE SURFACE: The Sleipner West natural gas field in the North Sea produces carbon dioxide. To avoid paying a tax on carbon dioxide emitted into the atmosphere, Statoil, which owns the field, has been injecting most of this carbon into a saline aquifer beneath the sea. A partnership that includes Statoil, other energy companies, North Sea countries and the European Union is monitoring the carbon dioxide to verify that it remains trapped in the aquifer.

or injected into the deep ocean. All of these approaches come with costs and risks, but the potential pay-off is enormous — a decarbonized energy future that does not involve total overhaul of our carbon-based energy.

One option, geological sequestration, is particularly attractive. Here, carbon dioxide is removed from industrial smokestacks and injected into subsurface reservoirs. There it would reside for long periods of human time — at least 500 years, a geological twinkling. To be effective, the carbon dioxide must be injected as a supercritical phase, a high-density material that forms at elevated temperatures and pressures. Supercritcal carbon dioxide is a high-density fluid phase with both liquid and gas properties, and would be stable at roughly 800 meters depth in most settings.

Anthropogenic carbon dioxide emissions total roughly 7 billion tons of carbon a year (7 gigatons per year), about 50 percent of the annual additions to greenhouse forcing. For sequestration to play an important role in mitigating greenhouse gas emissions, we must capture and store almost one-third of that, about 2 gigatons of carbon per year. As such, individual injection projects must bury on the order of one million tons per year, with all injection projects accounting for hundreds of millions of tons of carbon each year. Reaching this goal will require many injection projects spread over a large geographic area. In order to address a range of critical scientific and engineering questions raised by sequestration, we need to begin more large-scale projects now. Such projects will require industrial, academic, and governmental participation and support, with annual operating costs of tens of millions of dollars.

In the United States, one exceptional location to begin a large-scale project (about 1 million tons per year) is in the northern Rocky Mountains. Here exists an abundance of all the main classes of sequestration targets, including depleted oil and gas fields. In addition, carbon dioxide pipelines already crisscross Wyoming, Colorado and New Mexico to assist enhanced oil recovery projects. Many potential sequestration targets lie along the pipeline right-of-way, as do other significant carbon dioxide sources, such as coal-fired power plants. Finally, an unusually large supply of subsurface, public domain core, along with well and seismic data, are available for addressing some of the more immediate earth science questions. Currently, a consortium led by the University of Wyoming and Colorado School of Mines is investigating such a project. Other large-scale projects are being pursued in southern Texas, led by the Bureau of Economic Geology, and along the Ohio River valley, led by the companies American Electric Power and Battelle.

How to store carbon dioxide

Five different types of geologic reservoirs are suitable for storing carbon: saline aquifers, depleted oil and gas fields, unmineable coal seams, oil shales and mafic rocks.

Saline aquifers: Saline aquifers are bodies of porous, permeable rock that hold undrinkable, unusable brines. Estimates show that saline aquifers could be the largest reservoir, with the potential to hold between a total of 100 and 1,000 gigatons of carbon.

Supercritical carbon dioxide displaces pore fluids, and is trapped below an aquiclude or seal. This may either happen within a trapping configuration (such as a four-way closure) or in a dynamic trap, where aquifer downwelling prevents carbon dioxide escape. Potential targets exist in many states, and their capacity in the United States is large but incompletely mapped. This problem is even truer for other countries, including India and China, which have vast sequestration potential due to their Mesozoic and Cenozoic tectonic and stratigraphic histories. (Read more about saline aquifers on page 22 of this issue.)

Depleted oil and gas fields: Injecting carbon dioxide into a depleted oil or gas field can be a tool not only for storing carbon dioxide, but also for enhancing recovery of whatever oil and gas remain in the reservoir pores. As with a saline aquifer, the injected carbon dioxide displaces pore fluids, but here the presence of hydrocarbons affects the chemistry of the interactions among the rock, brine and gas. Commonly, carbon dioxide mixes with the remaining oil, expanding its volume and reducing its viscosity at depth. These factors can result in enhanced oil recovery (EOR). EOR projects using carbon dioxide have run for more than 25 years in the United States and Canada. In this process, most of the oil and carbon dioxide remain in the subsurface, effectively sequestering the gas.

> **The role of the geoscientist is clear: to work to better understand the real risks of leakage and hazards caused by carbon dioxide injection.**

A large project demonstrating EOR and carbon dioxide sequestration is running in Saskatchewan, Canada. The project, owned and operated by the EnCana oil company, stores the carbon dioxide in Weyburn, a giant oil field first produced in the 1950s. As part of a scheme to recover the additional reserves still in the ground, a 300-kilometer pipeline carries carbon dioxide from a gasified coal plant in North Dakota across the border for injection. Currently, 5,000 tons of carbon per day are used for EOR at Weyburn, roughly 800,000 tons per year. According to the operators and the U.S. Department of Energy (DOE), by the project's end in 2025, roughly 130 million barrels of oil will be recovered and 19 million tons of carbon will be stored at Weyburn.

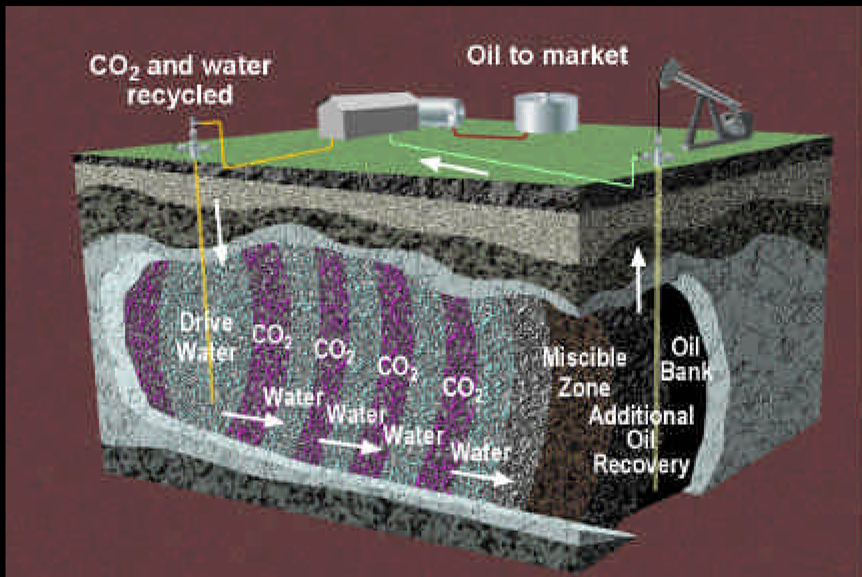
The economic incentive of extra fossil fuel production makes it likely that EOR will be the first widely deployed carbon storage strategy. The lifetimes of many depleted fields could be significantly extended through economic incentives for carbon sequestration. It is not clear, however, that the science and engineering that would maximize recovery would also maximize carbon storage. In addition, brine acidification can greatly increase corrosion of old wells, increasing the risk of unintended leakage or aquifer damage. Finally, brine chemistry is greatly complicated by the addition of carbon dioxide as a separate gas phase, which could affect mineral precipitation, dissolution, and brine salinity and pH. Significant research and industrial expertise is needed to best address the technical questions involved. Some of these questions will be studied at Weyburn, but much more investigation will be needed.

Coal seams and enhanced coalbed methane recovery: The majority of coal within the United States is unmineable. For the sake of discussion, an unmineable coal seam is deeper than 2,500 feet (the coal mine with the deepest vertical shaft in the United States is the Resources No. 5 mine in Alabama's Blue Creek coal seam, run by Jim Walter Resources. The shaft reaches 2,100 feet deep). In practical terms, coal cleats, the natural fracture system in coals, begin to shut at roughly 5,000 feet, significantly reducing permeability. So, the chief window for coal sequestration lies between 2,500 and 5,000 feet (about 800 to 1,600 meters).

At these temperatures and pressures, carbon dioxide adsorbs onto organic mineral surfaces. As it does so, it releases methane. In high-rank coals — which contain more energy than lower-rank coals — roughly two carbon dioxide molecules will adsorb to every one methane molecule released. This process enhances coalbed methane recovery, and is currently used in the Allison field development in northern New Mexico. Like EOR, enhanced coalbed methane production provides a production incentive to store carbon geologically.

Some new evidence from a U.S. Geological Survey team led by Bob Burruss and Hal Gluskoter suggests that in lower-rank coals, the ratios of carbon dioxide to methane may be more like six to one and in some cases as low as 17 to 1. If so, the lowest ranked coals release the least methane per unit of carbon dioxide, and as such, coalbed methane potential is inversely proportional to carbon dioxide storage potential.

A great deal of scientific uncertainty surrounds the processes and geological settings for coalbed sequestration. It is not clear, for example, how this process varies in the presence of other gases, such as nitrogen. Carbon dioxide seems to make coal cleats shut, reducing effective permeability. Nitrogen enhances coal cleat dilation and permeability, but has no sequestration potential. Thus, mixing gases has the potential to optimize sequestration and recovery, but more experimental and field



Courtesy of EnCana Corp.

OIL AND GAS, REDEFINED: This diagram shows how carbon dioxide is used to recover oil from EnCana Corp.'s Weyburn oil field in Saskatchewan, once considered depleted. The carbon dioxide is compressed and sent down a pipeline to the field from its source, the Great Plains Synfuels plant in Beulah, N.D. The compressed gas dissolves in the oil, reducing the oil's viscosity, swelling it and helping it move to the production well. Most of the oil remains, along with the carbon dioxide, making this enhanced oil recovery technique a candidate for geologic carbon sequestration.

After 15 years, EnCana probably won't need to purchase any more carbon dioxide from the Synfuels plant. It will recycle it from the oil and use that recycled carbon dioxide to continue enhanced recovery for another 10 or so years, says Malcolm Wilson of the Petroleum Technology Research Centre at the University of Regina in Saskatchewan, a group that is part of an international coalition monitoring the carbon dioxide at Weyburn. "The name of the game is to get as much oil as possible with as little carbon dioxide as possible," Wilson says.

Currently, EnCana is injecting an estimated 1 million metric tons of carbon dioxide per year into the field. That's about 40 percent of what is produced by the Synfuels plant, Wilson says. For more about Weyburn, read the story on page 24 of this issue.

research is needed to optimize this process. Similarly, more work is needed to understand how coal petrology affects the adsorption and release of gases. The deep structure of cleats, the primary permeability control, is not well understood. Moreover, there are no large-scale deployments of this technique, nor are there deep well tests beyond roughly 6,000 feet, the current theoretical limit. Finally, it is difficult to characterize capacity in these settings. Until many of these problems are better resolved, coal will remain a somewhat uncertain sequestration target. (See also the story on page 24 in this issue.)

Oil shales: The processes of adsorption in coals also work for the organic minerals in oil shales. Unfortunately, the scientific uncertainties are even greater, because oil shales demonstrate complex petrology and mineralogy and a great range of maturities. However, there are commercial shale gas producing fields, and there is a potential for oil shales as sequestration targets. As such, until enhanced oil shale recovery is attempted and adsorption experiments run, we will not have much of a feeling for the storage capacity of oil shales.

Mafic rock bodies: For many years, petrologists and geochemists have recognized that carbon dioxide can react with mafic minerals (e.g., olivine and serpentine). These reactions run so that carbonate replaces silica, taking up the carbon dioxide and permanently binding it as magnesite, ankerite and siderite. As such, there is potential to store carbon in mafic bodies by injecting carbon dioxide into deep fracture networks. Unfortunately, these reactions are very slow, requiring thousands of years, and are disequilibrium reactions, which means that many chemical assumptions may not hold. Moreover, little is known about fracture networks in specific target rock bodies. The Pacific Northwest National Laboratory, a DOE lab, is leading a plan for a pilot project in the Columbia flood river basalts to address some of the first-order scientific concerns. Columbia University is also preparing an experiment within the Palisades Sill. (See the story on page 24 in this issue for more on mafic rocks.)

Geologists are key

A quick examination of the reservoir list above reveals a great potential for scientific research. Skills ranging from structural geology, siliciclastic and carbonate sedimentology and stratigraphy, low-temperature geochemistry, petrography, and isotope geochemistry will be needed to address many of the outstanding questions in geological sequestration. Below is a list of a few of the more important questions that need answers:

Reservoir heterogeneity: As in the petroleum industry, reservoir heterogeneity will greatly affect the injected carbon dioxide stream. The distribution of porosity, permeability and large-scale connectivity associated with facies changes, diagenesis, stratigraphy and fracture characteristics are of critical importance to the success of any carbon dioxide storage effort. In addition, an improved understanding of multiphase flow through porous media is critical.

Sealing: Much depends on the viability of the cap rock, an impermeable rock layer that overlies a reservoir. If it does not seal well, then carbon dioxide will ultimately leak out of the reservoir. The strength and composition of the seal rock under different injection pressures is of critical importance. Perhaps of greater importance, permeable faults and stratigraphic bodies may compromise the seal rock locally, and are likely to have a dramatic impact on the success of any specific venture. Here, the experience of industry may prove invaluable.

Interactions among brine, rock and gas: The complex, multiphase chemistry of the subsurface is poorly constrained. Many important mineral precipitation and dissolution reactions are not well understood, and rates are poorly quantified. Even less is known about dynamic changes in the pH, salinity or composition affected by massive carbon dioxide injection. An army of geochemists and experimentalists is needed to tackle the problem.

Geomicrobiological interactions: Both methanogenic and sulfur-reducing bacteria live in the subsurface. They may play an important role in unmineable coal seams and in certain rock-chemical reactions involving carbon dioxide. To date, we lack a comprehensive catalog of such organisms, and do not understand the mechanics or kinematics of their metabolic behavior. This area represents a significant opportunity to advance understanding both in basic and applied biogeoscience.

Analogs: Large-volume, natural carbon dioxide accumulations occur in the United States, France, Australia and other countries. Often associated with magmatic sources, these represent natural analogs for large-volume storage of subsurface carbon dioxide and gas migration. In addition, several ancient provinces could have been ancient carbon dioxide provinces, such as the Denison Trough in eastern Australia. These locations have received relatively little study regarding their mineralogy, fluid migration history and diagenesis, and represent a unique opportunity for geologists to contribute to carbon sequestration learnings.

Many ways to store carbon

Geological sequestration has advantages because it is relatively low cost and low risk and many technologies for implementing it are already established. There are, however, many approaches to carbon storage that all have strengths and weaknesses.

Terrestrial Sequestration: Here, carbon is stored either in land biomass, such as forests, or in soils. These approaches — such as soil management practices that increase the amount of carbon a soil can take up — can be deployed today at very low costs in certain regions, and as such have received significant attention and research. Limiting features include the small potential reservoirs involved and difficulties in monitoring and verification. Finally, it is not clear how long carbon can be effectively stored in these systems.

Ocean Sequestration: This includes multiple approaches, such as increasing primary marine productivity in nutrient-limited regions and direct injection and storage of carbon dioxide as a liquid phase on the sea floor. The ocean represents the largest potential reservoir by far, and would store carbon dioxide for long time scales, more than hundreds of years. Unfortunately, serious concerns remain about the potential impact on marine ecosystems and ocean acidification, and about the carbon dioxide's eventual return to the atmosphere. These concerns have led some researchers to ask whether the best way to clean the atmosphere is to sully the ocean.

Advanced concepts: These include different developing approaches. One involves permanent chemical fixing of carbon dioxide as carbonate through chemical exchange, e.g. changing olivines or serpentines into iron and magnesium carbonates. Another possible approach involves genetic modification of carbonate fixing organisms, e.g., modified bacteria that would deposit aragonite from airborn carbon dioxide. These approaches would be permanent and easily monitored. Alas, they are also both very expensive, and these technologies do not work well today.

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Monitoring and verification: Economic and political concerns necessitate a strong monitoring and verification program for sequestration projects — specifically, to demonstrate success, calculate volumes and check for leaks. To date, the most successful and promising techniques are direct subsurface measurements based on geophysics, including 4-D reflection seismology, a proven industry tool. Other approaches, like electrical resistive tomography or microseismic arrays, need to be further explored and developed as potential monitoring tools.

Geologists will also be key players in communicating what geologic carbon sequestration really is. Geological carbon storage involves a non-volatile, non-flammable substance and the time scales are, geologically, small. As such, this approach is distinctly different from nuclear waste storage in terms of public risk and hazard potential. Nonetheless, it is possible for the public to draw inaccurate and incendiary parallels between the two efforts. In addition, any large-scale project would occur on, under or near public lands or population centers. If geologists do not make people aware of these projects early in a way to generate support, people could backlash against potential storage centers. Although the current science suggests that health and resource risks are likely to be small, there are reasonable concerns about leakage, shallow gas accumulation and infrastructure damage. We need to understand the possible risks and be able to explain them clearly.

Again, the role of the geoscientist is clear: to work to better understand the real risks of leakage and hazards caused by carbon dioxide injection. Efforts to improve monitoring and verification will help significantly, as will face-to-face contact between geoscientists, the public at large, and people who live near possible storage sites. In particular, our community will have to educate the public on the threat of global climate change, the importance of fossil fuels in our national energy framework and how carbon sequestration can help to solve the pressing dilemma before us.

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